Simulating EUV Emission from Laser-Produced Plasma

EUVL Workshop

LBNL, Berkeley, CA

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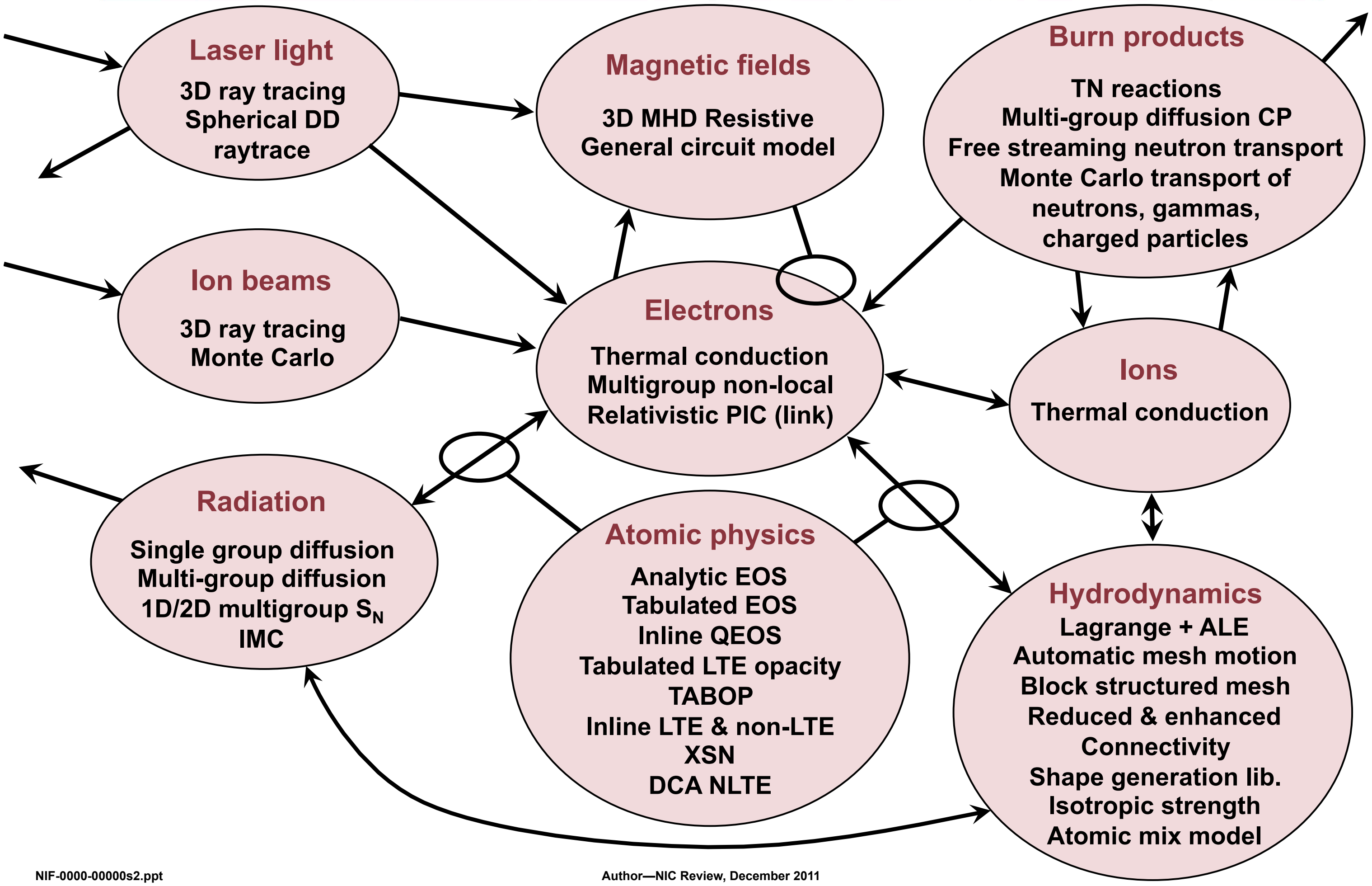
Computer simulations can speed up the development of EUVL sources

- Experimental results are the "gold standard" for EUVL sources.
- Experimental data has limits on spatial, temporal, and spectral resolution and can't answer all questions.
- It takes time and money to field a new EUVL source.
- The combination of experiment and simulation can improve EUVL sources faster than experiment alone.
- Simulations can be used to:
  - Perform parameter studies
  - Examine in detail conditions inside the target
  - Identify key physical processes
  - Provide initial experimental settings for a new EUVL source

Outline

- Discussion of simulations and HYDRA
- 1D simulations of a tin vapor target heated by a CO_2 laser.
- 1D simulations using a proposed thulium laser.
- Ensemble simulations
- Enabling the use of higher quality atomic models in HYDRA

HYDRA is used to simulate emission from Laser Heated Tin Targets



- Key features
  - Hydrodynamics
  - Laser ray trace
  - NLTE atomic physics
  - Radiation transport
  - 1D, 2D, and 3D simulations

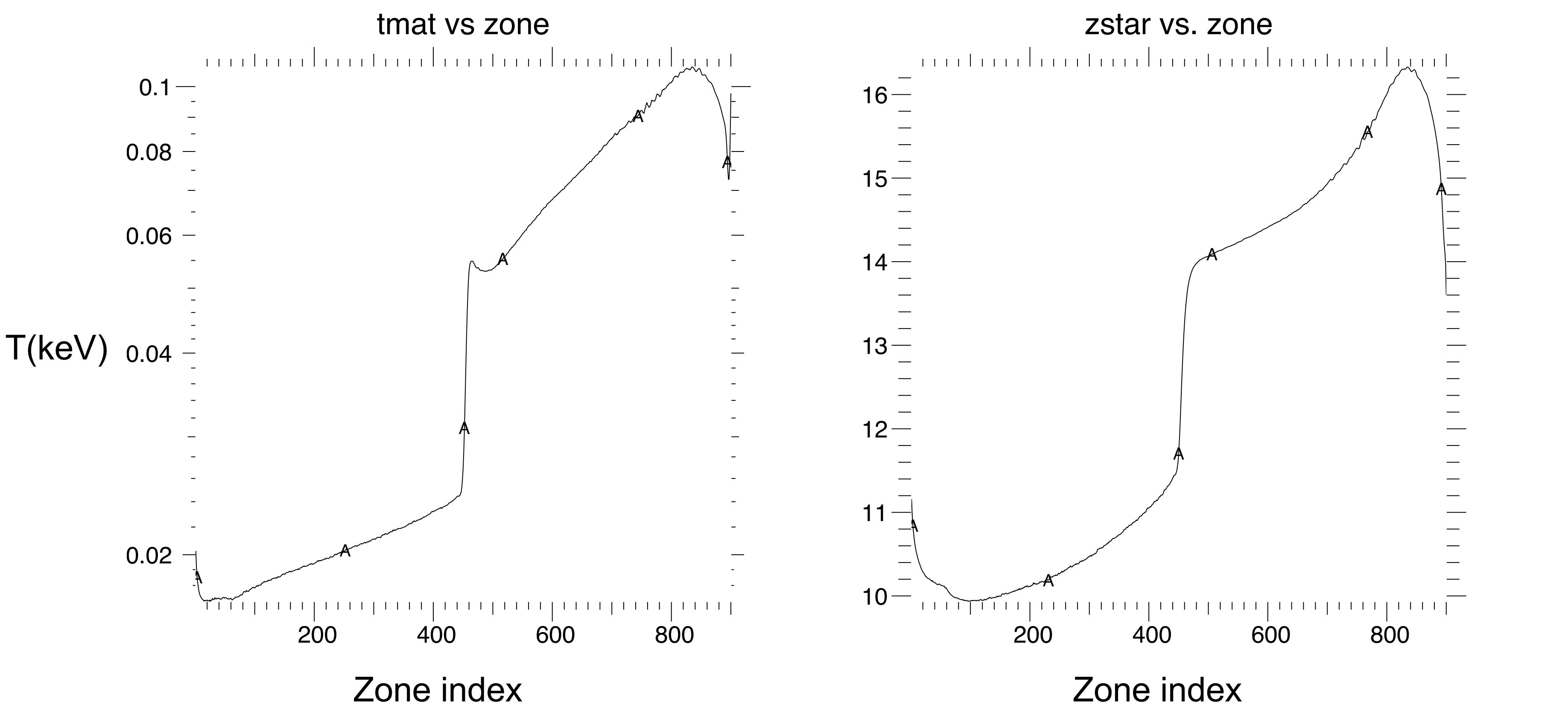
HYDRA computes a numerical solution to the laws of physics

- HYDRA numerically solves the partial differential equations on a grid.
- More complicated physics models and finer grids require more computer time.
- The designer running HYDRA uses his/her experience to judge which features must be included in the simulation and which can be skipped.
- The designer will scan a range of conditions using simple simulations, then run detailed simulations for the most interesting conditions.

Key features of the sample simulations

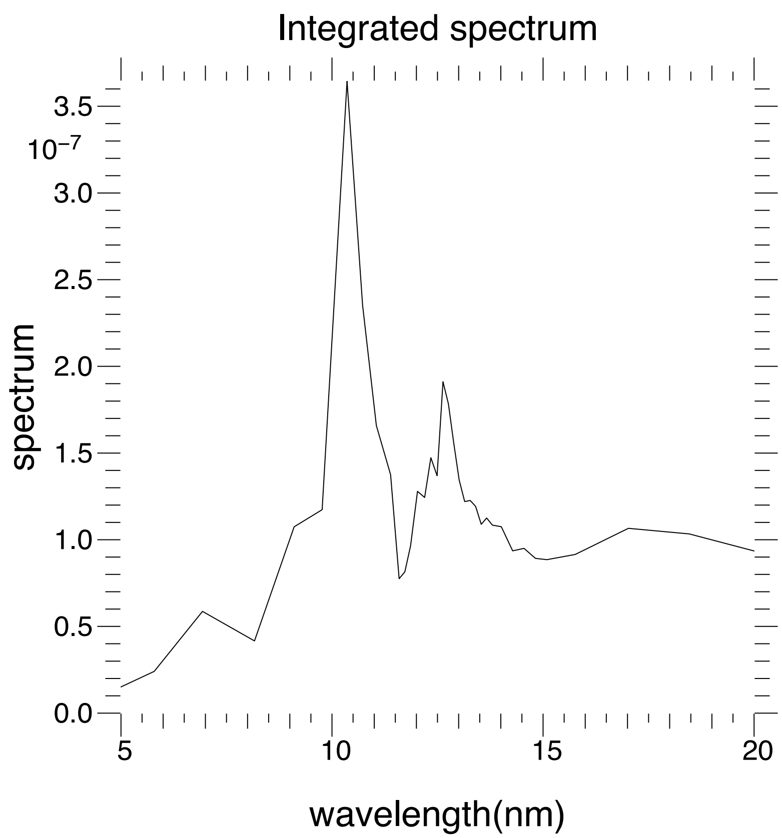
- Uniform tin vapor fills a cylindrical volume. (**not** a real target)
- The CO_2 laser has a flat-topped pulse, a smooth Gaussian focal spot, and is normally incident on the face of the cylinder.
- The simulations are 1D (vary only in the laser direction). This keeps the runtime low.
- non-LTE opacities and emissivities are required because the tin emission comes from low densities.
- Maximizing conversion efficiency requires setting the intensity so that the right ionization states are generated.
- To fully tune the CE, it is also necessary to vary the laser pulse duration and the target thickness.

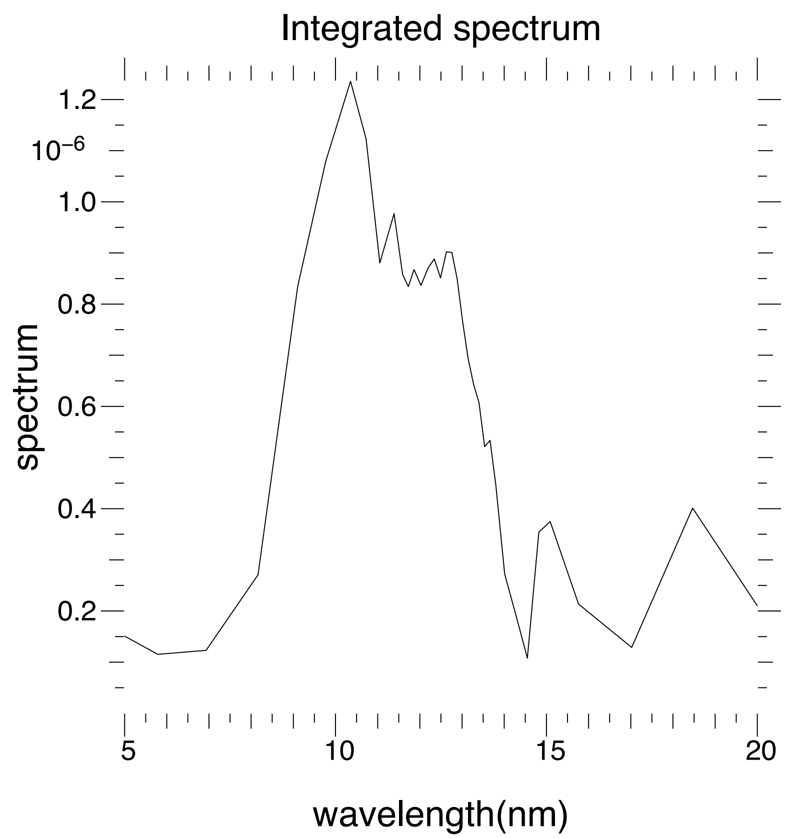
The 13.5 nm EUV emission is strongest at temperatures of 20-80 eV and z* 12-20.



- This plot is at 75 ns into a 113 ns pulse and the laser comes from the right.
- The 13.5 nm emission is due to n=4 to n=4 transitions in tin. If the temperature is too high, there will not be enough n=4 electrons.

The time-integrated EUV spectrum changes as the laser intensity changes

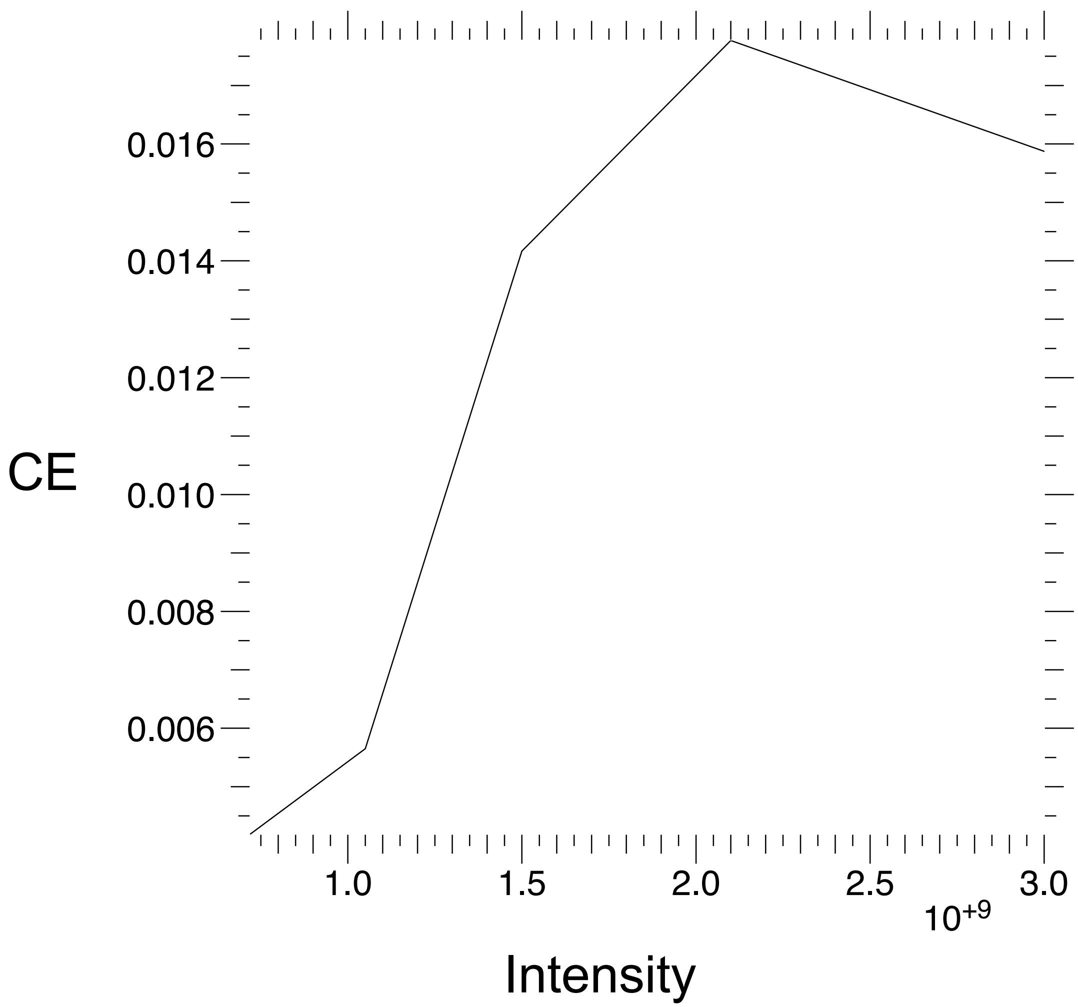




$I_{las} = 1.05 \times 10^9$ W/cm^2

$I_{las} = 3.0 \times 10^9$ W/cm^2

The EUV conversion efficiency depends on the laser intensity

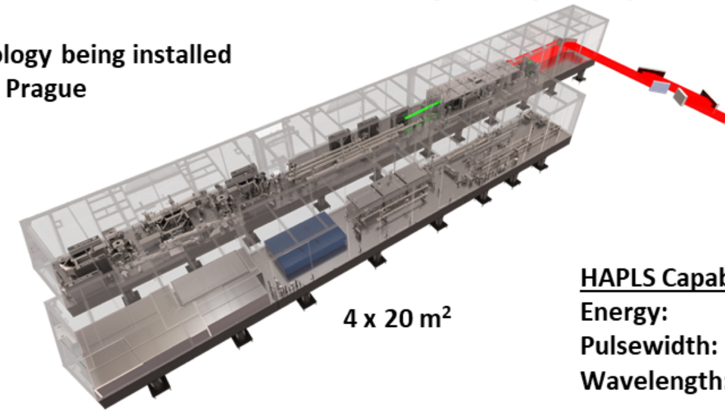


- The ratio of EUV bandpass emission to laser energy peaks near $2x10^9$ W/cm^2.
- The emission in the 13.5 nm bandpass is still increasing above $I=2x10^9$ W/cm^2.

LLNL's architectures for Petawatt lasers scale to hundreds of kW average power, advancing scientific frontiers

High-repetition-rate Advanced Petawatt Laser System (HAPLS)

1 PW @ 10 HZ
Operational technology being installed
at ELI-Beamlines in Prague



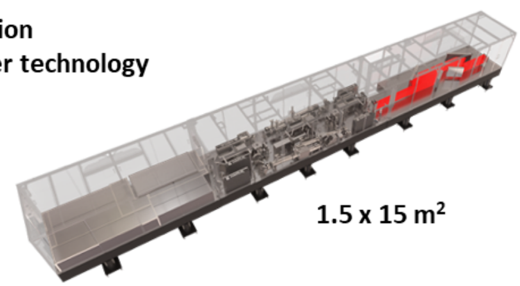
4 x 20 m^2

HAPLS Capabilities

Energy:	30 J
Pulsewidth:	28 fs
Wavelength:	820 μm

Scalable High-power Advanced Radiographic Capability (SHARC)

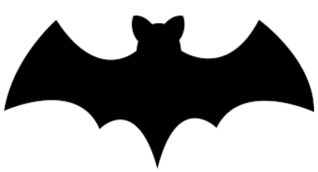
1 PW @ 10 HZ
Direct implementation
of HAPLS pump laser technology



1.5 x 15 m^2

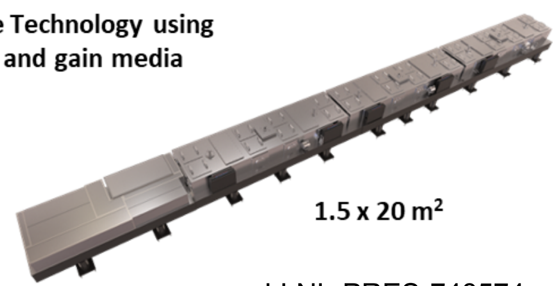
SHARC Capabilities

Energy:	150 J
Pulsewidth:	150 fs
Wavelength:	1.053 μm



Big Aperture Thulium (BAT) System

0.3 PW @ 10 kHZ
High TRL HAPLS-like Technology using
Commercial Diodes and gain media



1.5 x 20 m^2

BAT Capabilities

Energy:	30 J
Pulsewidth:	100 fs
Wavelength:	1.95 μm

300 W
Indirect CPA
Max E-O Efficiency 1.5%

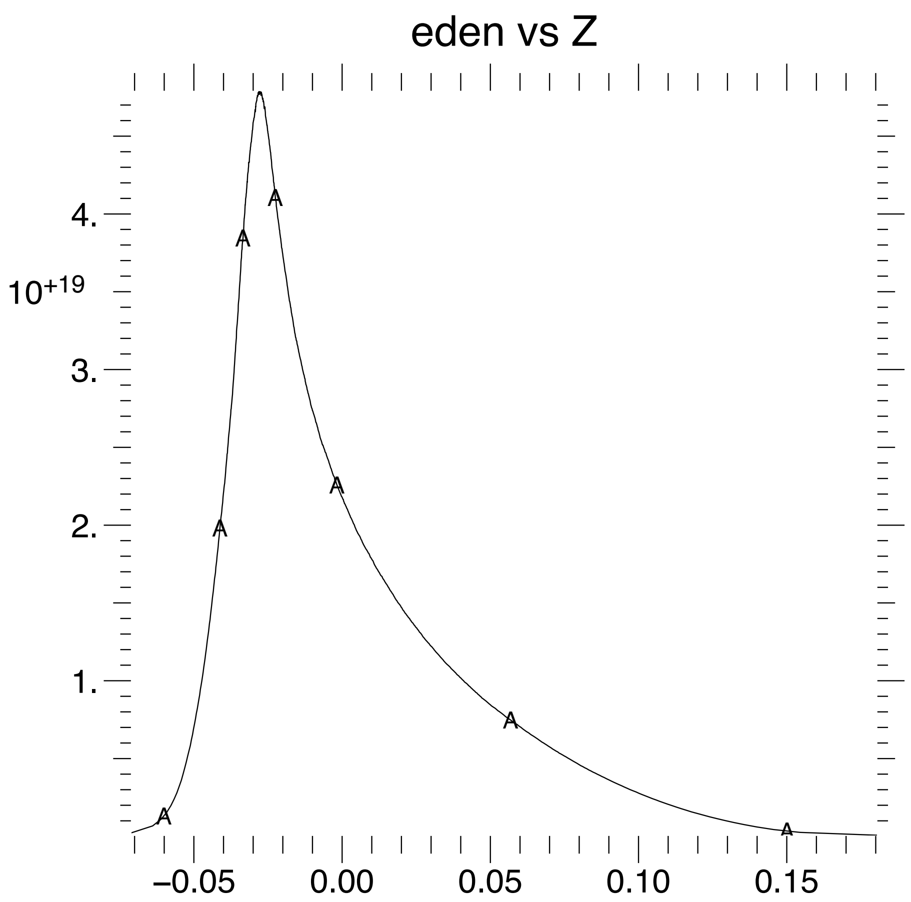
1,500 W
Direct CPA
Max E-O Efficiency 7.6%

300,000 W
Direct CPA
Multi-pulse Extraction
Max E-O Efficiency 21%

LLNL is developing solid state lasers that might work well for EUV sources

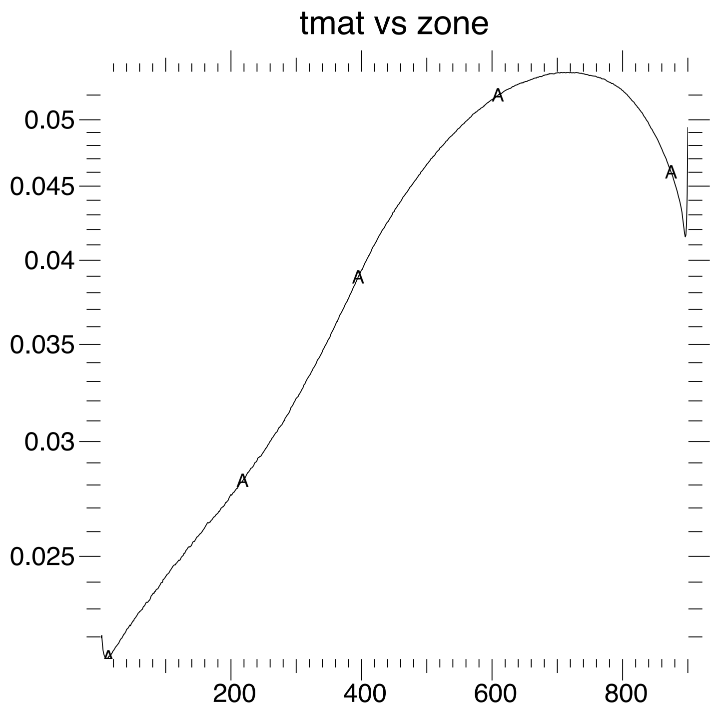
- LLNL's thulium laser design has higher average power (~300 kW) than commercial CO_2 lasers (~20 kW).
- The pulse-to-pulse jitter is less than 1%.
- Thulium lasers can deliver pulse durations of ~100 ns and can have excellent temporal shaping capabilities.
- The thulium laser wavelength is 1.9 um vs. 10.6 um for CO_2. Does this help or hurt conversion efficiency?
- Simulations can be used to assess the potential of thulium lasers without the expense of building and fielding one.

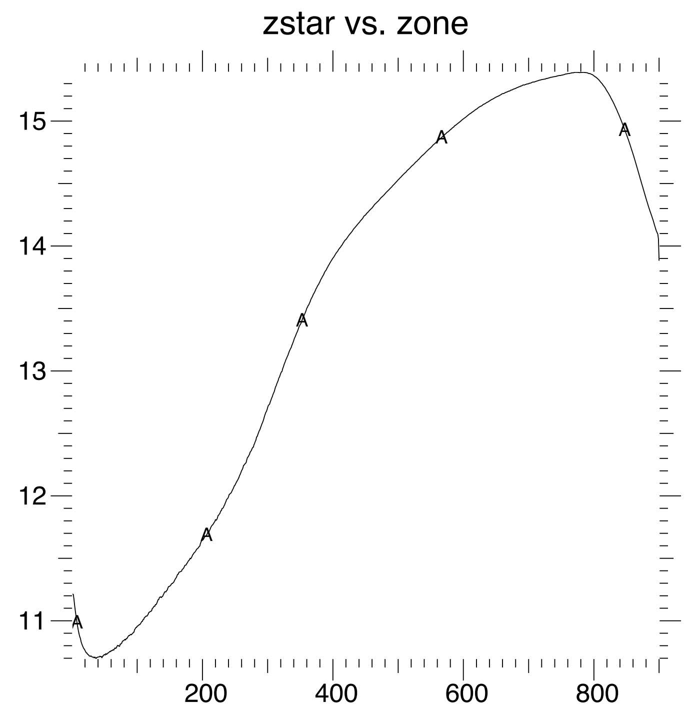
Changing the laser wavelength changes the required tin vapor density



- Light cannot propagate through a plasma when the electron density exceeds the critical density.
- The critical density for a 1.9 um Thulium laser is 3.0×10^{20} cm^{-3} while it is 9.8×10^{18} cm^{-3} for a CO_2 laser.
- The electron density in this simulation is too low to stop the thulium laser.

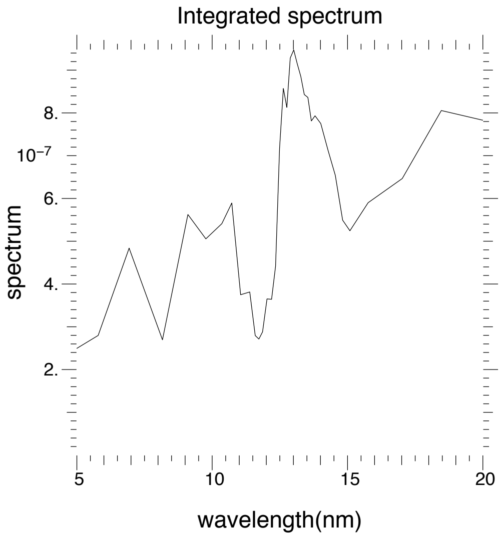
Simulations using a thulium laser drive the plasma into conditions where it emits 13.5 nm EUV.





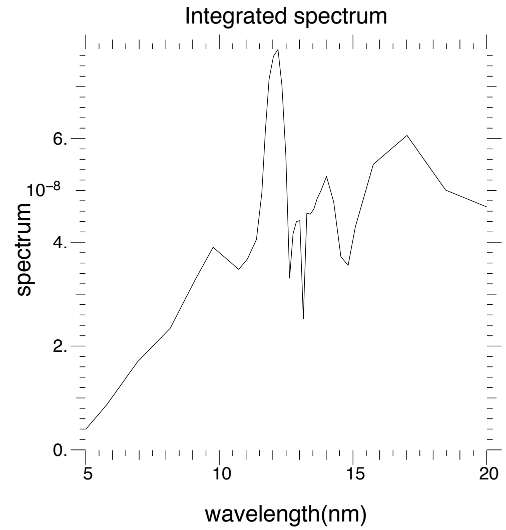
- The 13.5 nm emission is strongest for temperatures of 20-80 eV and z* 12-20.

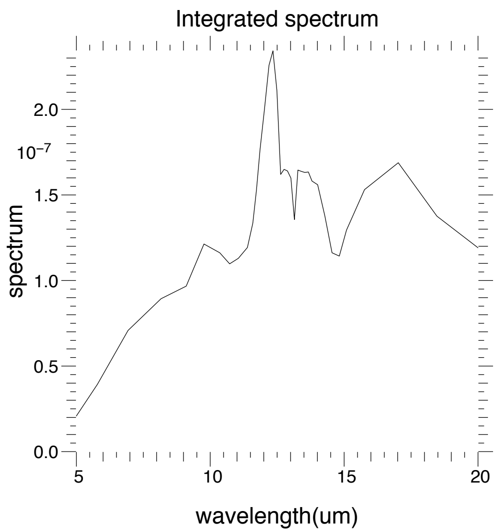
The 13.5 nm EUV emission varies with the laser intensity



I_{las}=2.1e9
CE = 7.5%

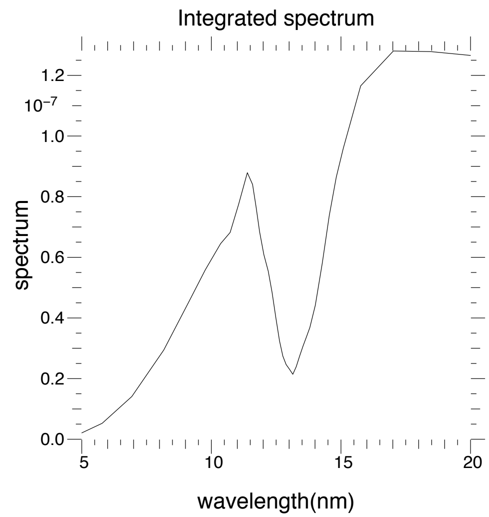
I_{las}=1.35e9
CE = 6.5%





I_{las}=1.11e9
CE = 4.5%

I_{las}=0.4e9
CE = 0.92%



- The highest conversion efficiency is 7.5% for I_{las}= $2.1\text{x}10^9$ W/cm^2.
- Pulse lengths vary.
- This exceeds the CE of the best CO_2 simulation in this series.

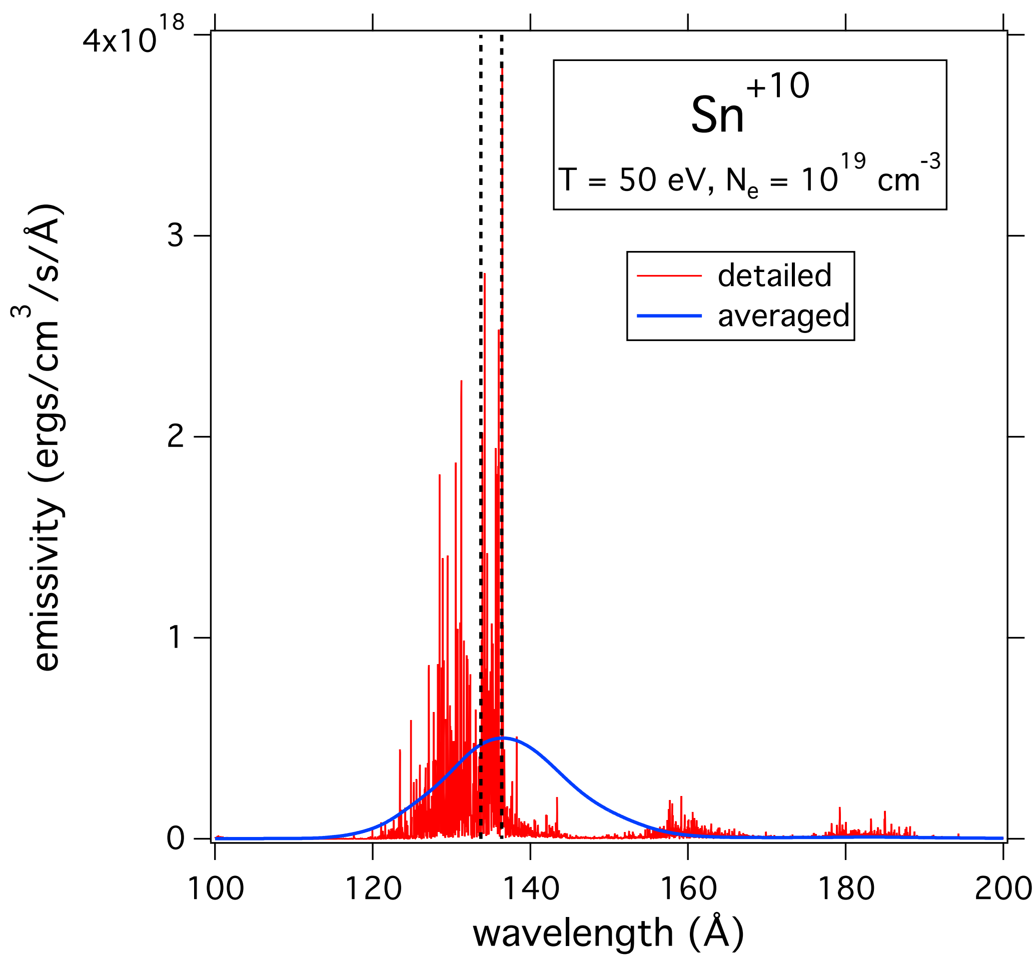
LLNL is developing efficient ways to run large ensemble simulations

- Manually tuning a capsule with one parameter is tedious. Simultaneously tuning multiple parameters is impractical.
- Ensemble frameworks automate running many simulations with varying target and laser parameters.
- Our framework has been used to run a 2D HYDRA ensemble with over 60,000 NIF capsule simulations.
- The results are fit with a surrogate model that can be evaluated anywhere in the parameter space.
- Surrogate models are much faster than running HYDRA, so they are well suited for optimization studies.

Ensemble simulations can be used to optimize the target and laser pulse

- This summer we will run a 1D ensemble simulation where the parameters are the target thickness, the laser energy, and the laser pulse length.
- Trial runs with 300 EUV source simulations have been completed.
- The surrogate model will be used to find the highest conversion efficiency in the 3-dimensional parameter space.
- We will then run 2D simulations near this “optimal” point.

Modest sized atomic models blur emission enough that it is hard to get the right amount in the 13.5 nm bandpass



Averaged model before adjusting amount in bandpass

- The detailed model has a very large number of lines in the 110-170 Angstrom region. It is too slow for inline use in HYDRA.
- The (smaller) averaged model is fast enough for inline use and gets the correct total emission, central energy and RMS width, **but** underestimates the emission in the 13.5 nm bandpass.

The non-LTE opacity package in HYDRA is being upgraded to allow complex atomic models to be used inline

- non-LTE atomic physics can take 60% of the run time for the averaged model.
- The detailed model has ~5X more levels and takes ~35X longer to run.
- The NLTE package is being ported to Nvidia GPUs. This should boost performance 5-10X over the CPU-only version on LLNL's new Sierra system.
- We currently have a 5X speedup and hope to do better.
- We should be able to run HYDRA simulations with the detailed model and get the right fraction of the emission in the 13.5 nm bandpass without adjustments.

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